Comparison of the effect of ASR deterioration on the load carrying capacity of concrete structural elements in accelerated laboratory tests and in the field

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Abstract

Alkali-silica reaction (ASR) is a long-term deterioration for reinforced concrete structures, particularly after 15 to 25 years of construction. To assess the reactivity of aggregates currently 4 accelerated test methods, namely, Accelerated mortar bar test (AMBT), Concrete prism test (CPT), Accelerated concrete prism test (ACPT) and Ultra-accelerated concrete prism test (UACPT) are carried out from very short durations of a few days up to 2 years. Both in Australia and overseas, currently, research is being conducted on accelerating the CPT by increasing the testing temperature from 38°C to 60°C and this test is referred to as the ACPT. In ultra-accelerated autoclave tests (UACPT) carried out to date, the mixes were boosted with alkalis between 1.5 to 3.5% by mass of cement and maximum temperatures used by different researchers varied between 111°C and 150°C. In all these tests only one cycle of autoclaving was carried out. Based on this information, a new multi-cycle autoclave test method for ASR is being investigated at the University of Technology Sydney on boosted (to 2.5%) concrete prisms and reinforced concrete beams. The maximum temperature was maintained at 80°C for a duration of 60 hours for each cycle and three cycles were applied over a period of 9 days. Measurements were taken after each cycle and the details of this procedure are presented in this paper. This UACPT test, on prisms of actual concrete mixes, is able to simulate expansion and cracking caused by ASR. Significant expansions and ASR damage were observed which simulated long-term ASR deterioration effects in the field. A multi-cycle autoclave test method appears to be suitable for investigating ASR deterioration of actual concrete mixes, by testing plain and reinforced concrete elements of up to 340mm long, within a short period of time.

Keywords: *alkali silica reaction (ASR); load capacity reduction; reinforced concrete; ultra-accelerated concrete prism test*

1. INTRODUCTION

Alkali-silica reaction (ASR) is a potential source of deterioration of concrete. Damage due to alkali-silica reaction (ASR) in concrete is a major durability problem for concrete structures and has been observed as such in many countries around the world [1]. Concerns were raised about the residual load capacity of structures due to ASR damage in the concrete. Stanton [2] who investigated some premature failure of concrete pavements and partial failure of bridge structures in California, reported that the excessive expansion due to a chemical reaction inside the concrete was the predominant factor that induced tensile stresses exceeding the tensile strength of concrete. This was identified as Alkali-Silica Reaction. Since then, numerous papers pertaining to this deleterious chemical reaction, or alkali-silica reaction have been published, including researches on reaction mechanism, test methods, effective methods to mitigate potential ASR and structural behaviour of ASR affected concrete structures. Various models including theoretical approaches, mesoscale or macroscale models have been developed by different authors to predict the ASR effects.

Alkalis in concrete basically initiates ASR, mostly from Portland cement as well as other internal and external sources which causes high concentration of alkalis within the pore solution. The alkalis initially attack some siliceous phases in aggregates and alkalis produces an expansive gel, consequently causing expansion and cracking of concrete and ultimately reduces the mechanical properties [2]. In the existing two laboratory test methods, namely AS 1141.60.1 [3] accelerated mortar bar test (AMBT) and AS 1141.60.2 [4] concrete prism test (CPT), AMBT can produce results within 21 days. CPT, however, takes 1 year for OPC concrete mixes and 2 years for mixes with Supplementary Cementitious Materials (SCM). In both methods, aggregates are crushed to give specific grading. Also, AMBT test requires handling of NaOH solution at 80°C.

In order to test concrete mixes as used in the field and also to study reinforced concrete elements, an ultra-accelerated test method is required. An autoclave environment is suitable for this purpose. Autoclave test methods for determining the potential alkali silica reaction have been investigated by several researchers [5-10]. In these autoclave test methods, the mixes were boosted with alkalis between 1.5 to 3.5% by mass of cement. Maximum temperatures used in these methods were kept between 111°C and 150°C. Duration of the test was between 4 to 24 hours for concrete prisms and 2 to 6 hours for mortar bars.

In the field of predicting and assessing of the structural performance of ASR affected concrete structures, considerable amount of research work has been performed. Researches on load carrying capacity of ASR affected reinforced concrete beams, however, show some contradictory results. On one hand, reduction of material properties such as elastic modulus, tensile strength and compressive strength of concrete material were reported due to alkali silica reaction in concrete and on the other hand, experimental studies performed by different researchers showed that the residual load carrying capacity of the ASR affected beams was not significantly affected or even slightly increased indeed. However, comparing to the service life of a structure, these tests are only a snapshot in time. The long-term effects of ASR on the load carrying capacity of the structure is still unclear. A reliable analytical tool to assess capacity reduction due to ASR, especially the long-term effects of ASR is thus needed.

2. EXPERIMENTAL PROCEDURE

2.1 Materials used, Mix design and preparation of specimens

A general purpose Portland cement with equivalent alkali content (Na_2O_{eq}) of 0.50% by mass of cement was used for all specimens. Equivalent alkali content was calculated as Na_2O+0.658K_2O. The cement oxide composition analysis is provided below (Table 2.1).

Table 2.1: Cement oxide composition

CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	MgO	TiO_2	P_2O_5	Mn_2O_3	Na_2O_{eq}	LOI
64.18	19.67	4.78	3.10	2.37	0.91	0.22	0.06	0.12	0.50	4.09

For non-reactive sand, Sydney sand was used and as coarse aggregate a highly reactive 20mm Dacite was used. The chemical composition of reactive Dacite aggregates is given in Table 2.2.

Table 2.2: Chemical composition of Dacite aggregates (% by mass)

CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	TiO_2	P_2O_5	Mn_3O_4	BaO	Na_2O	K_2O	LOI
2.35	68.38	13.25	3.32	1.30	0.36	0.08	0.06	0.03	2.41	3.84	4.52

The mix proportions used for all specimens is given in Table 2.3.

Table 2.3: Mix Proportions of concrete

Material	**Quantity (kg/m^3)**
Cement	520
Non-reactive sand	620
20mm reactive aggregates	1160
Water	192.5
Sodium Hydroxide pellets	13.69

To boost the Na_2O_{eq} in the concrete mix to 2.5% level (by mass of cement), sodium hydroxide pellets with purity of 98% were added to the mixing water 24 hours prior to mixing (of the concrete) and the closed plastic container was left in the laboratory overnight at about 23°C. This is to avoid the heat generated during the dessolution of the sodium hydroxide pellets so that the mixing water for concrete was at about 23°C. The concrete was mixed in a horizontal pan mixer with a capacity of 70 litres and plain 100mm dia x 200 mm cylinders, 75x75x285mm size prisms and 100x100x340mm reinforced concrete beams were cast. The position of 8mm diameter deformed bar reinforcement in the 100x100mm cross-section of the beams is shown in Figure 2.1.

The following day, the specimens were demoulded and the initial length and mass readings of the prisms with studs were recorded for expansion measurements and change of mass. All the specimens were then stored in a temperature-humidity controlled cabinet kept at 23°C and 90% R.H. until testing. At the age of 28 days the specimens were taken out and tested as described in Section 2.2.

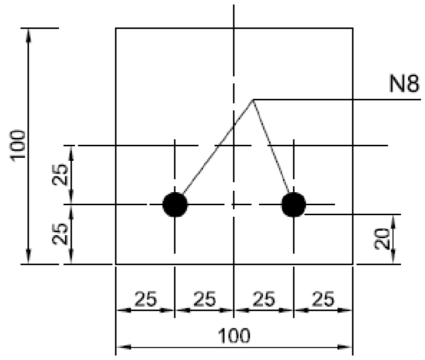

Figure 2.1: Reinforced concrete beam cross-section

2.2 Test Procedure

At the age of 28 days the specimens were removed from the cabinet and tested as described below. The 100mm diameter cylinders were used for the measurement of compressive strength and modulus of elasticity at the age of 28 days in accordance with AS 1012.9 [11] and AS 1012.17 [12], respectively.

The prisms were taken out of the cabinet and the lengths and masses were recorded and then placed in the autoclave (Zirbus LVSA 50/70 model with a chamber volume of 153 litres) for accelerated temperature cycles. Selected number of cylinders and the reinforced concrete beams were also placed in the autoclave as shown in Figures 2.2 and 2.3.

Figure 2.2: Autoclave used for the test

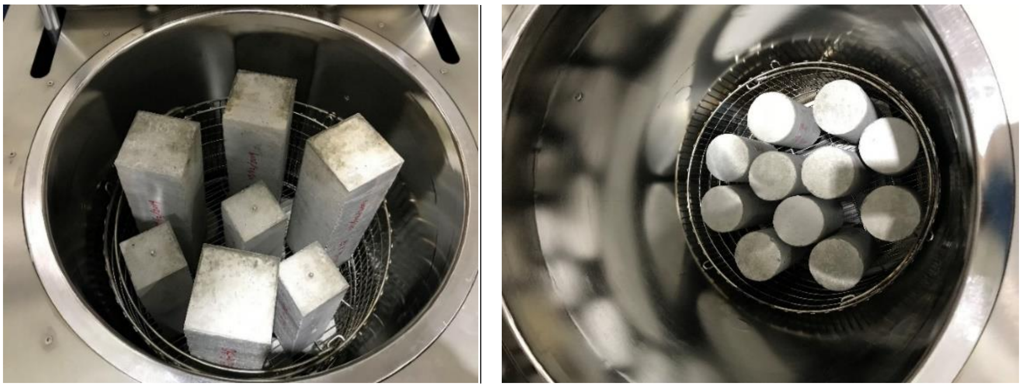

Figure 2.3: Specimens as placed in the autoclave

Initially a temperature cycle of 130ºC at a pressure of 170 kPa was adopted. However, as the effect of temperature-pressure combination was not clearly established other combinations at 95ºC, 80ºC and 70ºC were considered systematically. At these temperatures below 100ºC, the specimens did not experience any surrounding pressure. Finally a testing regime of 3 cycles at a maximum temperature of 80ºC was adopted as shown in Figure 2.4.

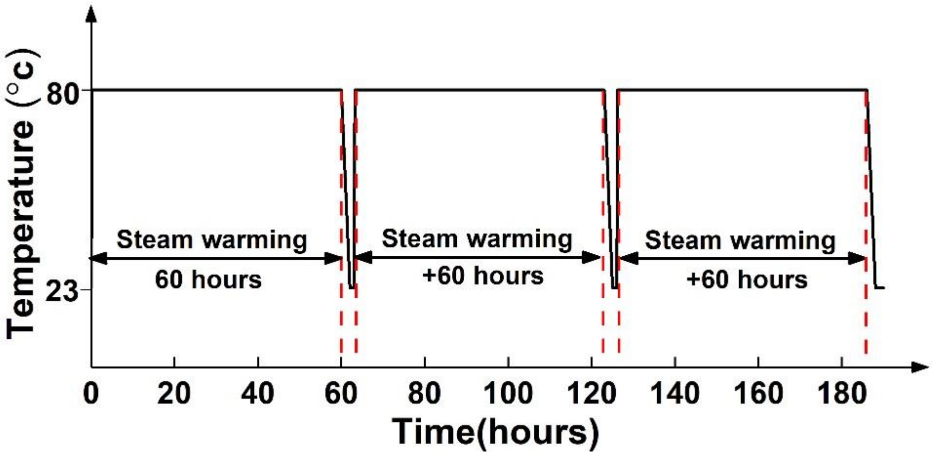

Figure 2.4: Temperature cycle adopted in the autoclave chamber

At the end of each cycle the expansion of the prisms, due to accelerated ASR reaction was recorded and the next cycle was applied. At the end of each cycle, 3 cylinders and 1 reinforced concrete beam were taken out for mechanical property testing and load capacity testing. The reinforced beams were tested under 2-point loading as shown in Figure 2.5.

Figure 2.5: Testing of reinforced beams under 2-point loading

3. RESULTS AND DISCUSSION

3.1 Cracking of specimens and assessment of ASR

The crack patterns of concrete cylinders and prisms, with 2.5% Na_2O_{eq} boosting after 3 cycles in the autoclave are shown in Figures 3.1 to 3.3. Enlarged micrographs of internal cracks and white deposites of similar specimens are shown in Figures 3.4 and 3.5.

Figure 3.1: External cracks on cylinders after 3 cycles in the autoclave

Figure 3.2: External cracks on prisms after 3 cycles in the autoclave

Figure 3.3: Enlarged view of external cracks on prisms

The external cracks resembled the map pattern ASR cracks observed in the field. Further characterisation of external cracks are currently underway using a 3D Digital Image Correlation (DIC).

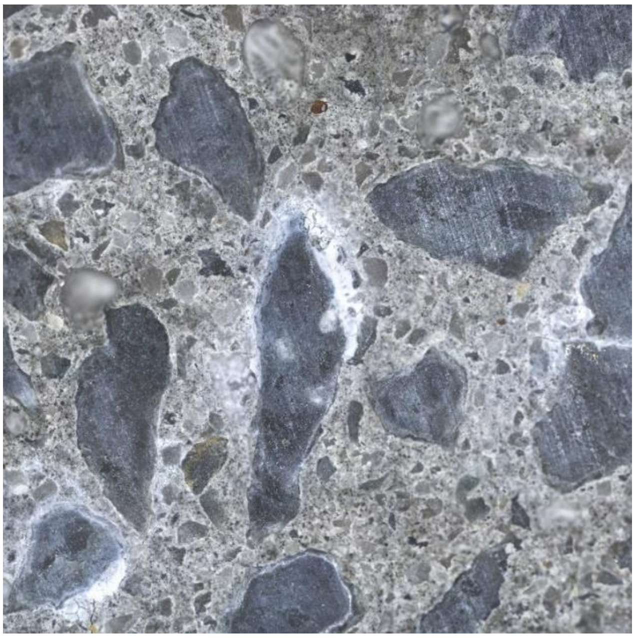

Figure 3.4: Internal cracks and white deposit on similar prisms after 3 cycles in the autoclave

After the 3 cycles in the autoclave sections of specimens showed white deposites around aggregates (Figure 3.4) and within cracks through aggregates (Figure3.5). Chemically these were analysed to ensure ASR gel formation. The morphology of these products may be different to what is formed in the field over longer period of time. This aspect is further investigated.

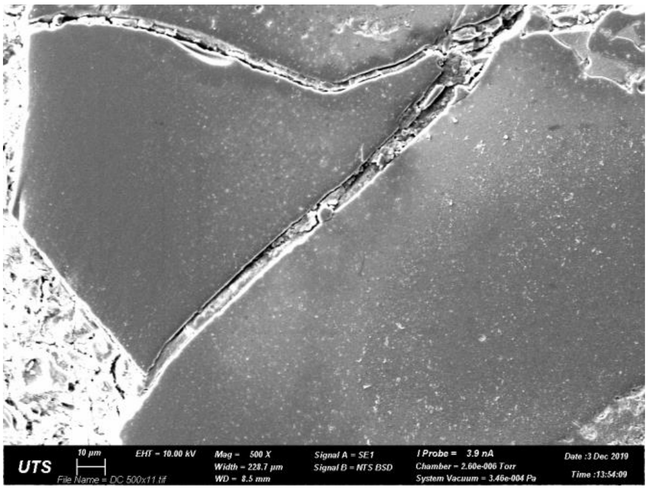

Figure 3.5: SEM of cracks through aggregates and ASR gel formation after 3 cycles in the autoclave (Magnification 500 times)

The expansion of the concrete prism is caused by components of expansion due to internal micro-cracking, cracking at boundaries of aggregates and cement paste and external macro-cracking. The expansion results and its effect on mechanical properties are discussed below.

3.2 Expansion and mass change

Expansion of the concrete prisms from the time of demoulding and after 3 cycles in the autoclave is shown in Figure 3.6. In the temperature-humidity controlled cabinet, during storage up to the age of 28 days a slight shrinkage of 0.019% was observed. After the 3 cycles in the autoclave, a total expansion of about 0.18% was recorded. The prisms showed external macro-cracks and internal micro-cracks as discussed in section 3.1.

The accompanying mass change of the prisms is shown in Figure 3.7. The prisms gained about 0.4% mass during the storage in the cabinet and after the 3 cycles in the autoclave. The mass is measured immediately after removing from the cabinet or autoclave while the specimens are fully saturated.

The ultra-accelerated autoclave based concrete prism test used in this study is able to simulate expansion and cracking caused by ASR within a short period of time. Significant expansions and ASR damage were observed which simulate long-term ASR deterioration effect in the field. An innovative multi-cycle autoclave test method appears to be suitable for investigating ASR deterioration.

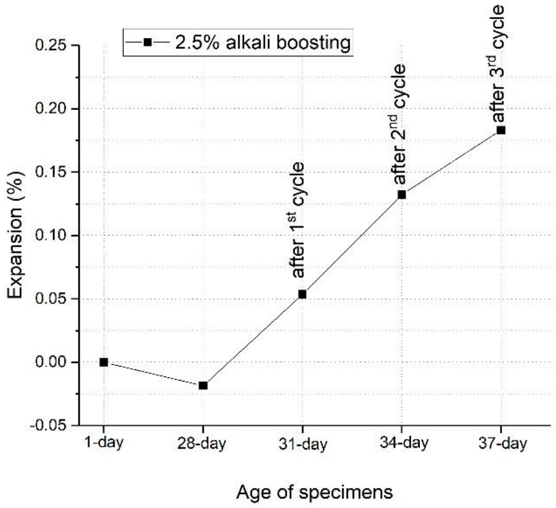

Figure 3.6: Expansion of concrete prisms after 3 cycles in the autoclave

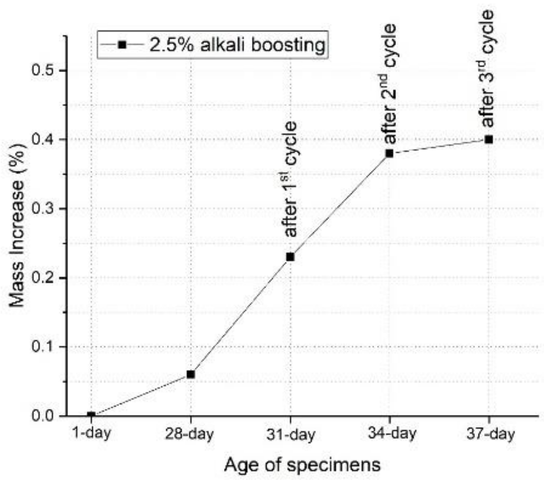

Figure 3.7: Mass change of concrete prisms after 3 cycles in the autoclave

3.3 Mechanical properties

3.3.1 Modulus of Elasticity

Modulus of elasticity is considered as the most sensitive mechanical property affected by ASR. The results after 3 cycles in the autoclave are shown in Figure 3.8. The modulus of elasticity decreased with each cycle as expected and after 3 cycles a reduction of 40% was recorded from the initial value. The reduction is caused by micro-cracking of the material due to accelerated ASR.

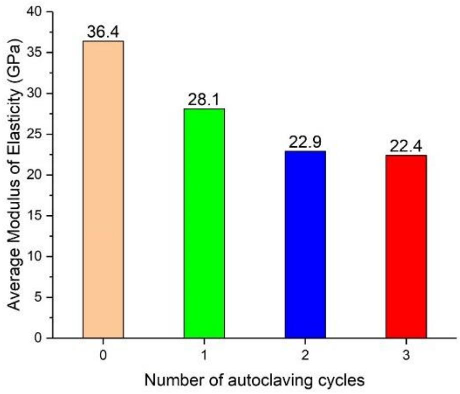

Figure 3.8: Change in modulus of elasticity of concrete cylinders after 3 cycles in the autoclave

3.3.2 Compressive strength

The compressive strength results are shown in Figure 3.9 and no dis-earnable changes are noticed. This is being further investigated.

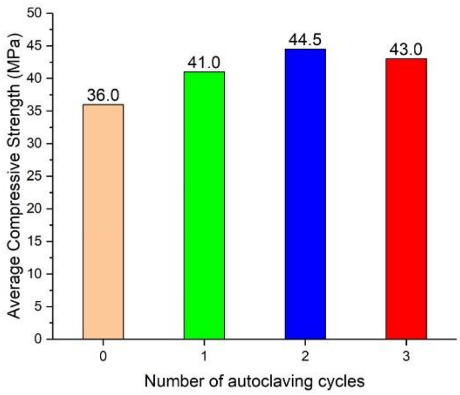

Figure 3.9: Change in compressive strength of concrete cylinders after 3 cycles in the autoclave

3.4 Load capacity

To study the reduction in load capacity reinforced beams of various configurations are tested. Initial results of a beam failed in shear is shown in Figures 3.10 and 3.11. Almost all reinforced concrete beams of the size and reinforcement ratio tested failed in shear. Currently, beams with different span to depth ratios are tested. Some of these beams are expected to fail in flexure. Both flexural and shear capacity are being studied.

Figure 3.10: Testing of reinforced concrete beams after each cycle in the autoclave

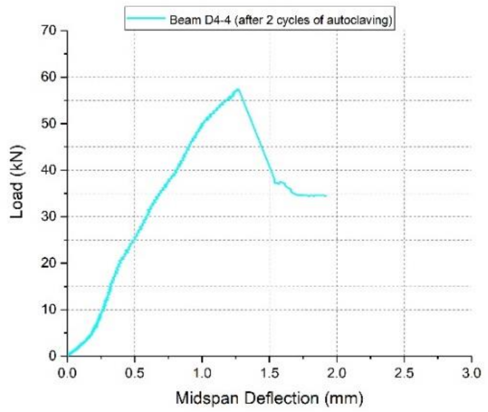

Figure 3.11: Typical Load-Deflection curve for the beam

A typical set of results of reinforced concrete beams tested are shown in Figure 3.12. Further investigation is continuing. Some reduction in failure load after each cycle is noticed.

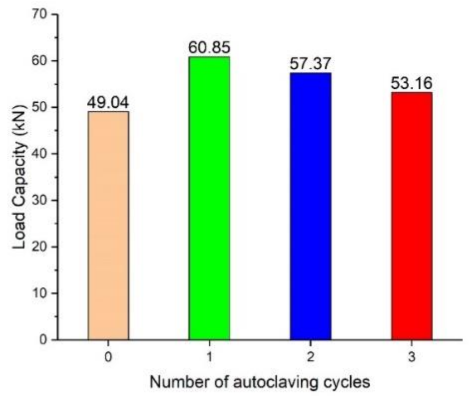

Figure 3.12: Typical results of reinforced concrete beams testing after each cycle in the autoclave

4. CONCLUSIONS

From the above study, the following conclusion can be reached at this stage.

- Ultra-accelerated test using an autoclave, with appropriate heat cycles, produces damage and expansion on boosted concrete elements due to ASR within a short period of 37 days of age.
- Evaluation of external macro-cracking and internal micro-cracking, together with expansion measurements can characterise the damage due to ASR and can be linked to the deterioration of the mechanical properties of concrete.
- Modulus of elasticity of the boosted concrete made of reactive aggregates, systematically decreased with increasing number of heat cycles.
- Load capacity reductions due to flexural and shear failure of ASR affected reinforced concrete elements can be studied using ultra-accelerated tests in an autoclave. Although currently structural members such as 3m long beams are tested in controlled climate chambers, a large scale autoclave can facilitate rapid evaluation of actual structural members affected by ASR.

5. ACKNOWLEDGEMENT

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